Commissioning of the ATLAS Reconstruction Software with First Data

A. Gibson, on behalf of the ATLAS collaboration

***Abstract*—Looking towards first LHC collisions, the ATLAS detector is being commissioned using all types of physics data available: cosmic rays, beam-halo and beam-gas events produced during LHC single beam operations. In addition to putting in place the trigger and data acquisition chains, commissioning of the full software chain is a primary goal. This is interesting not only to ensure that the reconstruction, monitoring and simulation chains are ready to deal with LHC physics data, but also to understand the detector performance in view of achieving the physics requirements. Cosmic rays have allowed us to study the ATLAS detector in terms of efficiencies, resolutions, channel integrity, and alignment and calibrations. They have also allowed us to test and optimize the muon combined performance algorithms.**

I. Introduction

ATLAS is one of two general purpose experiments being prepared for the Large Hadron Collider (LHC) [1] at CERN. The formal proposal for ATLAS was introduced in 1994, and detector installation in the cavern began in 2004. As detector installation proceeded detector commissioning began, first with individual sub-detectors and then with larger slices of the entire detector. As an integral part of this commissioning process we have also commissioned the reconstruction software. This is a necessary ancillary of the commissioning of the sub-detectors, and an integral part of the commissioning of the ATLAS experiment.

The ATLAS collaboration is large, with some 2500 physicists, from around the world, on the author list. The ATLAS detector [2] is also quite large, as seen in Figure 1. The general layout is fairly typical of a general purpose collider detector. We begin, closest to the beam pipe, with tracking systems in the inner detector: silicon pixels [3] and strips [4], and a transition radiation tracker [5] [6] with particle ID capability. The inner detector rests inside a two Tesla solenoidal magnetic field. Outside the solenoid are the calorimeters. The electromagnetic calorimeter [7] uses liquid argon as an ionization medium, with the absorbers arranged in an accordion geometry. The central hadronic calorimeter [8] uses a scintillating tile technology. Outside the calorimeters ATLAS has a large and impressive muon spectrometer [9]. The precision detectors are monitored drift tubes, and there are central and forward trigger chambers. The precision muon detectors include cathode strip chambers in the forward region, but these are not yet taking data. The muon spectrometer rests inside a toroidal magnetic field.

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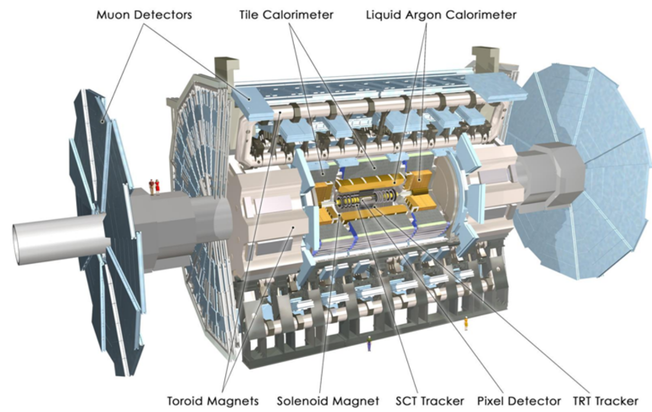

Fig. 1. The ATLAS detector. Several human figures, barely visible, are included for a scale reference.

Over the last two years we have conducted a series of integrated commissioning exercises, called "Milestone Weeks". During these Milestone Weeks we take all available sub-detectors, at least partially installed and commissioned, and operate them as an integrated detector, triggering and recording cosmic ray events. Of course reconstruction software is needed to support the effort. The last of these Milestone Weeks ("M8") was in July 2008. Other recent ATLAS commissioning milestones include first operations with full magnetic fields in August, three well publicized days of LHC single beam activity September 10-12, and, shortly thereafter, the first cosmic ray data with pixels.

The ATLAS reconstruction software framework is Athena [10], adapted from LHCb's Gaudi [11]. It is used for a variety of purposes, including high-level triggering, simulation, reconstruction, monitoring, and of course offline analysis.

The reconstruction flow begins with a source of data. This can be simulated data, or from the actual ATLAS detector. Simulated data begins with a generator, to be discussed below. Interactions with the detector are simulated with GEANT4 [12] and digitized by emulating ATLAS' electronic readout. A variety of reconstruction algorithms are applied to the raw data. The reconstructed data are then passed to clients such as online and offline monitoring applications, or offline analyses. All of these stages are fed by a detector description and a conditions database. The detector description records the position of all ATLAS components. The conditions database records quantities like detector voltages, pressures, temperatures, and calibration parameters, all as they depend on time.

This reconstruction framework must then operate in a variety of environments. This includes running online: for the high-level trigger, monitoring, and event displays. And it includes running in the complete ATLAS computing environment, including using the Grid. The Tier 0 center, at CERN, is used for prompt reconstruction: first of a small fraction of the data, the "express stream", and later the bulk of the data with refined calibrations. Dedicated calibration centers feed their results back to the Tier 0 and Tier 1 centers. The Tier 1 centers are responsible for the reprocessing of the data, with improved calibrations. And Tier 2 and Tier 3 centers play a role in Monte Carlo production and data analysis. For cosmic reconstruction we do not use the rapid, 24 hour, calibration loop that will be used for collisions. But, we have exercised all four tiers of the ATLAS computing environment.

The program of commissioning the ATLAS reconstruction software is to adapt this reconstruction framework to the evolving ATLAS commissioning environment. This adaptation will form the basis for the remainder of this discussion.

II. Software Commissioning with First Data

A. Simulation

To support data analysis and detector commissioning it is useful to be able to produce simulated data for a variety of commissioning scenarios. This can include generating particles for cosmic rays, from single beam scenarios such as beam halo and beam gas, as well as from colliding beams. Through the commissioning period the detector itself also continually evolves. The coverage increases, the magnetic field environment changes, and the detector even moves. For example, the endcap calorimeters have been moved by as much as four meters out of their nominal positions to allow easier access for electronics installation and commissioning. And, for alignment studies, it is useful to simulate various misaligned detector descriptions. These different scenarios affect how you generate, simulate, and digitize events, and how you reconstruct both Monte Carlo and real data. If the endcaps move the events need to be re-simulated. If the muon spectrometer coverage changes, merely because of changes in what is read out, then these can be realized by simply re-reconstructing the events.

As a concrete simulation example, consider cosmic ray data - the most common type of commissioning run. It is helpful to be able to efficiently simulate cosmic ray events, but many cosmic rays that reach the Earth's surface never deposit energy in the ATLAS detector. A typical scenario is to begin with a range of cosmic rays, 10 GeV to 5 TeV, randomly distributed on the surface in a 600 meter by 600 meter square. The generated muons are only simulated if they initially point to a sphere, radius 20 meters, centered at the nominal ATLAS interaction point. These muons are then simulated as they pass through the 100 meter rock overburden, including details such as the large asymmetric shafts used to lower ATLAS components from the service. If the simulation deposits energy in the ATLAS detector, or optionally a particular sub-volume of the detector, the event is digitized and recorded. One comparison between actual and simulated cosmic ray data

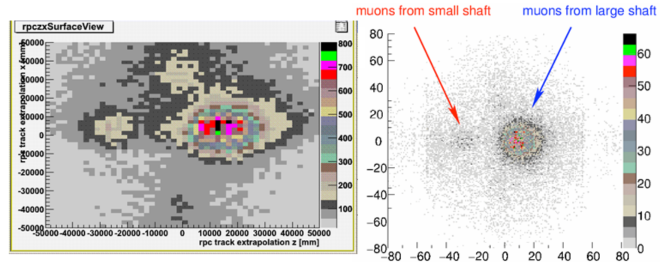

Fig. 2. Cosmic rays from data [left] and simulation [right]. The muons are reconstructed in the central muon trigger chambers (resistive plate chambers, RPC's) and extrapolated to the surface. Their extrapolated surface position is plotted [in mm on the left, and in m on the right]. The effect of the two large access shafts are clearly seen in data and simulation. In data we see two other areas of excess which correspond to smaller elevator shafts, not modeled in the simulation.

is shown in Figure 2. Muon tracks are reconstructed in the resistive plate chambers, the central muon trigger chambers. These tracks are then extrapolated to the surface of the earth. The effect of the two large access shafts is clear, and appears reasonably well modeled. But, in the actual cosmic data two other features are obvious. These correspond well to elevator shafts that were not included in the simulation.

B. Monitoring and Event Displays

The full ATLAS reconstruction software runs online to provide monitoring plots and event displays for the shift crews in the control room.

The monitoring plots are useful for monitoring the status of the detectors and data stream in real time, and for establishing the quality of the data. These plots include low-level checks of the integrity of the data and of simple quantities like detector occupancies and energies. But, they also include plots of relatively sophisticated derived quantities, and of correlations between detectors. In Figure 3 we plot the difference in a track parameter, ϕ, as measured in the muon spectrometer and inner detector. We see a reasonable correlation in the tracks measured by the two systems. At times, during detector commissioning, sub-detectors lose synchronization. For example, the muon spectrometer might systematically read out a different event than the inner detector. This particular plot was produced offline, but a loss of synchronization can be quickly observed with a similar online monitoring plot.

Examples of the most commonly used 2D event display, Atlantis [13], will be discussed later, in Figures 6, 7, and 11. Figure 4 shows a beam halo event from LHC single beam data, visualized in 3D with the ATLAS "Virtual Point One" (VP1) package. This event appears to be an interaction with beam-line components well upstream of ATLAS leaving muons traveling roughly parallel to the beam-line. These are then noticeably deflected in ATLAS' magnetic fields. The event displays are used online and offline. They are projected on the walls of the control room and useful as quick check online. Offline they are helpful for detector commissioning, for developers of reconstruction algorithms, and for physics analysis.

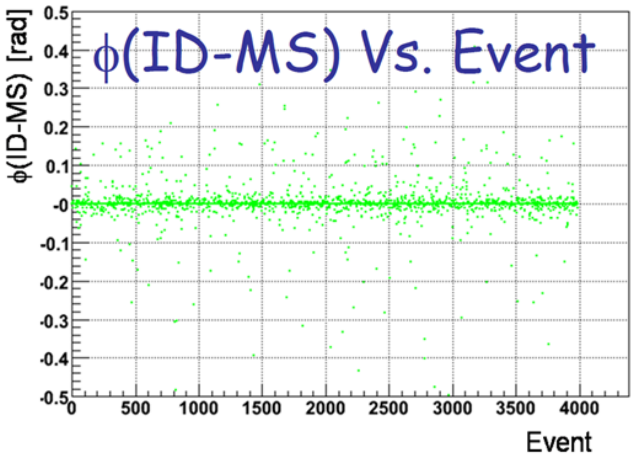

Fig. 3. The difference in the track parameter ϕ, as measured in the muon spectrometer and the inner detector, for cosmic ray data. This particular plot was produced offline, but a loss of synchronization can be quickly observed with a similar online monitoring plot.

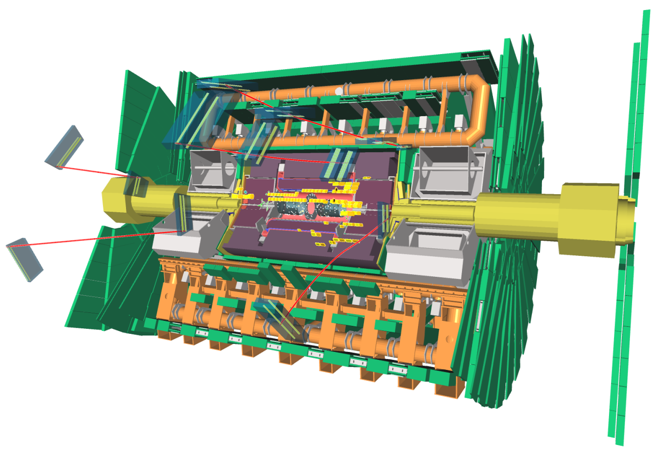

Fig. 4. A beam halo event from single beam data. Visualized with "Virtual Point One" (VP1).

C. Calibration and Alignment

An important part of commissioning the ATLAS software has been its usage for detector calibrations and alignments. The High Level Trigger selects event streams to align the tracking systems, and many detectors take dedicated calibration runs. The alignment streams are passed to dedicated computing facilities, where they must return a first pass alignment measurement within 24 hours. This first pass alignment is used for the bulk physics reconstruction at the Tier 0. A few months are then available to produce a refined, "best effort" alignment for use in the reprocessing of physics data at the Tier 1 centers. The entire procedure has been tested extensively with Monte Carlo simulation. Aspects of it are used also for the cosmic ray data, but without the strict 24 hour turnaround time. An early example of alignment from cosmic ray data can be seen in Figure 5. It shows an alignment based on just one day of cosmic data. These results will be much improved with additional data [14], but are already a significant improvement over the nominal alignment.

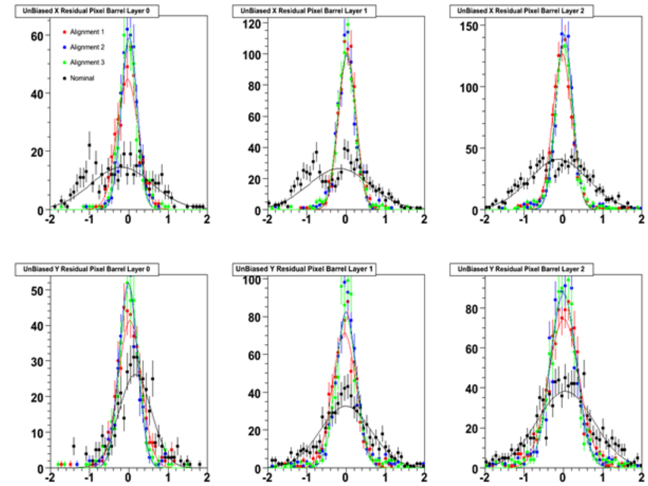

Fig. 5. X and Y residuals, in mm, for the three pixel layers. Using one day's worth of cosmic ray data a first alignment is produced. Three alternate alignment algorithms are compared to the nominal, pre-cosmic, alignment. Any one is a clear improvement, and they will be greatly improved with additional data.

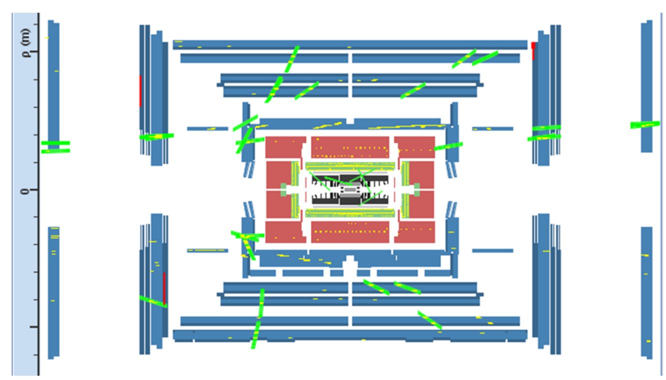

Fig. 6. An active beam halo event with muons swept up in the toroidal magnetic field. The solenoid was off.

D. Reconstruction Algorithms

While commissioning ATLAS with cosmic rays and single beam data, we use a variety of reconstruction algorithms. Some are the same as for colliding beam reconstruction, while others must be adapted to the commissioning environment. For example, we have taken data in a wide variety of magnetic field conditions: various combinations of solenoidal, and barrel and endcap toroidal fields, all at nominal and less than nominal strengths. For cosmic and single beam data we have no nominal interaction point, such as we will have for collision data. So, this constraint must be removed from tracking algorithms. Atlantis [13] event displays demonstrating tracking in varying magnetic field conditions are shown in Figures 6 and 7. It is also important to have reconstruction algorithms that are robust against noisy channels and other detector problems. Figure 8 shows an example of a track reconstructed while ignoring a noisy module in the silicon strips.

Another complication for reconstruction algorithms in the commissioning phase is the lack of event synchronization with an accelerator clock. With colliding beams we will know, rather precisely, when collisions occur. But, cosmic

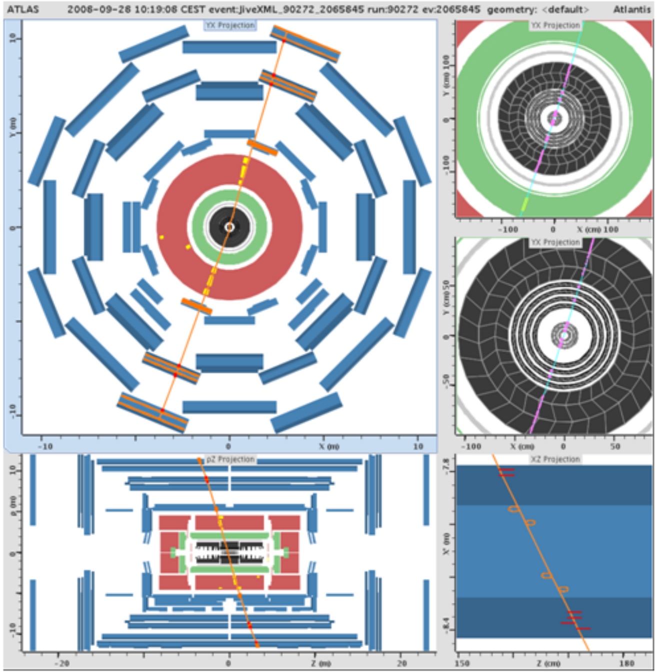

Fig. 7. A cosmic ray event with all magnetic fields, hits in all central ATLAS detector, and a combined track. On the left we see two global views. On the right we see: on the top hits in the EM calorimeter and inner detector, in the middle hits in the transition radiation tracker, silicon strips, and pixels, on the bottom hits in the muon spectrometer.

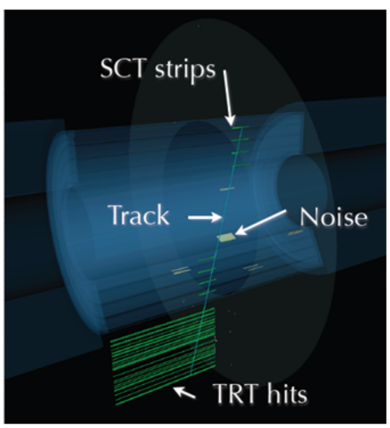

Fig. 8. A cosmic ray track reconstructed in the inner detector while ignoring a noisy module in the silicon strips (SCT) module.

ray, and often even single beam, events occur randomly with respect to the 25 ns clock cycles. For colliding beam reconstruction, the calorimeters will reconstruct their digital pulse shapes by means of optimal filtering coefficients [15] and take advantage of their knowledge of the collision time, and detailed knowledge of the pulse shapes. For commissioning, the tile calorimeter has instead use a three parameter fit for the pedestal, amplitude, and event time of each pulse. For its commissioning reconstruction, the liquid argon calorimeter uses an iterative application [16] of the optimal filtering coefficients for high amplitude pulses, effectively fitting for the event time. The effect on tracking detectors with a drift time is similar. For example, the inner detector reconstructs tracks twice for each event: once to determine the event-by-event time offset, and then again knowing the offset.

The iterative application of the optimal filtering coefficients for the liquid argon reconstruction, and other specialized reconstruction for commissioning, has significant implications for computing resources. The iterative optimal filtering for more than 180,000 liquid argon channels is CPU intensive. For each of these channels the optimal filtering coefficients and other calibration constants require hundreds of megabytes of RAM. For commissioning runs, the liquid argon frequently reads out more than the nominal five bunch crossings of digital data for each event, which puts further demands on the reconstruction as well as on the trigger and data acquisition chains. All of this increases the complexity of the computing exercise during the commissioning era, and makes it difficult to extrapolate CPU and memory requirements into the collision era. For collisions, a fixed-time optimal filtering algorithm will be applied to five samples of digital data in the liquid argon electronics, along with most of the other channel-level calibrations. So, the demands on the offline reconstruction will be significantly reduced.

E. Detector Performance Studies

Another important client of the reconstruction software is the commissioning of the ATLAS sub-detectors. They have all made good use of the available cosmic and single beam data sets. The liquid argon and tile calorimeters have each been able to select a sample of cosmic ray events with well understood energy signatures. Selecting a set of projective cosmic rays in the liquid argon calorimeter, we expect minimum ionizing muons to have a characteristic energy loss depending on the thickness of the calorimeter, which varies with pseudo-rapidity. Fitting the measured energy to a Landau distribution, the overall scale and the η dependence agree with simulation as shown in Figure 9, within an estimated 5% systematic uncertainty. The tile calorimeter takes a different approach, fitting a tile-only track to each cosmic ray candidate and not requiring a projective signature. They then normalize the energy deposit to the thickness of the detector along the track. We are able to make stringent tests of the energy scale and uniformity, as shown in Figure 9.

Another category of performance studies looks at correlations between sub-detectors. Figure 10 shows the momenta of tracks in cosmic ray events as measured by the inner detector and muon spectrometer. First, there is a reasonable correlation between the two measurements and a fair agreement between data and Monte Carlo. The effect of energy lost in the solenoid and calorimeters is also clear. Tracks observed in the muon spectrometer lose typically a few GeV in the solenoid and calorimeters before they are measured in the inner detector. For tracks in observed in the bottom of the muon spectrometer the opposite is true.

F. "Beam Splash" Events

One interesting category of events delivered by the LHC during single beam tests have been dubbed "beam splash" events. For a few hours the LHC delivered the entire beam of approximately 10^9 protons on a collimator located about 140

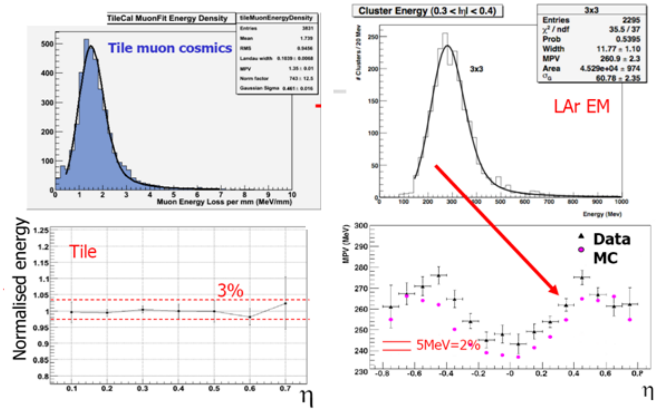

Fig. 9. Top Left: Energy deposited per mm by cosmic rays in the tile calorimeter. Bottom Left: Uniformity of cosmic ray energy deposits in the tile calorimeter. Top Right: Energy deposited by projective cosmic rays in a cluster of cells in the liquid argon calorimeter, for a particular bin in η. Bottom Right: Energy deposit in the liquid argon calorimeter as a function of η, and compared with simulation.

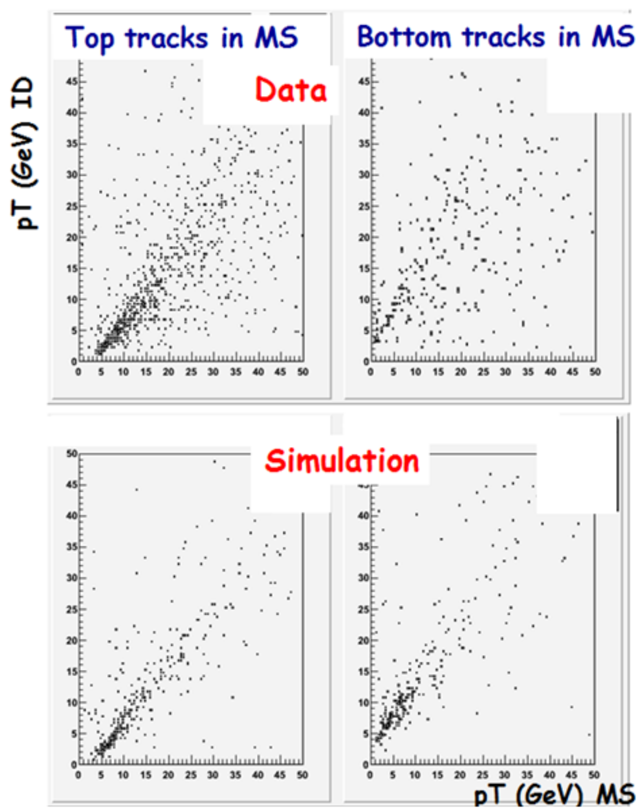

Fig. 10. Transverse momentum of cosmic rays as measured in the inner detector and the muon spectrometer. For data and simulation, and for tracks measured in the top of the muon spectrometer separated from those measured in the bottom. The effect of energy loss in the solenoid and calorimeters is clear.

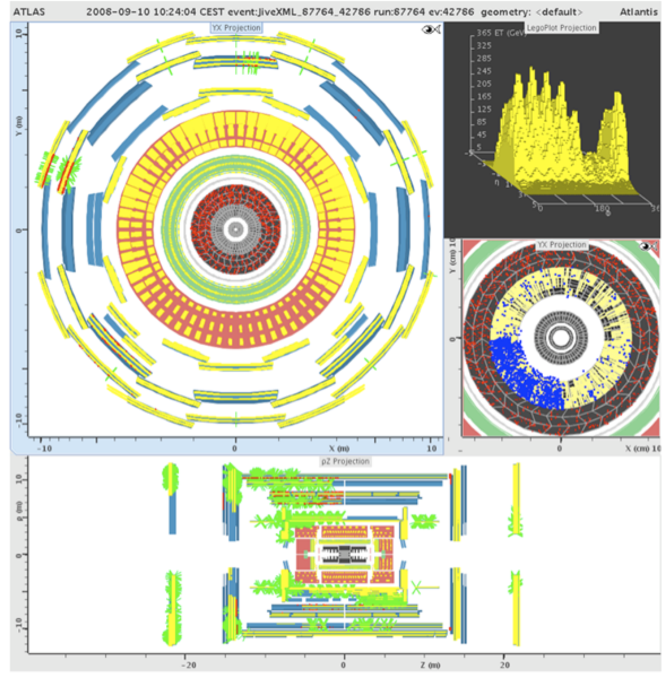

Fig. 11. A "beam splash" event from the first minutes of LHC single beam data at ATLAS. Approximately 10^9 protons were incident on a collimator located about 140 meters upstream of ATLAS. More than 1000 TeV of energy was reconstructed in the calorimeters. The various sub-detectors were not yet well timed with the specialized beam pickup trigger used, which explains the empty regions in the muon spectrometer and endcap calorimeter.

meters upstream of ATLAS, which showered a huge number of secondary particles throughout the detector. One of the first of these events, with the detector timing not yet well tuned for the beam pickup trigger, is shown in Figure 11. Dozens of these events were recorded with more than 1000 TeV of reconstructed energy in the calorimeters, hundreds of thousands of hits in the muon spectrometer, etc. They are perhaps the highest energy events ATLAS will ever record. With hits in nearly every channel these events are very useful for timing studies. The interactions were not synchronized with the LHC clock, but all of the particles in each collimator event are correlated in time with each other. Using these events, the transition radiation tracker was able to establish their inter-channel timing at the one ns level. An example of timing studies with the tile calorimeter is shown in Figure 12, where the inter-partition timing is measured, and the calibration of the intra-partition timing is tested.

These "splash" events are also very useful for detailed studies of signal pulse shapes, and for investigations of problematic detector channels. And, they provide a useful stress test of the ATLAS software. Despite the unexpected and enormous detector occupancies, the reconstruction software did not crash on any of these events. This robustness is due to the long experience with the reconstruction of cosmic ray and other commissioning data. From January to October 2008 more than 500 million events were recorded and reconstructed at the Tier 0 in more than 750,000 reconstruction jobs. The quality of the reconstruction software has been greatly improved as a result of this processing of the commissioning data. For example crashes due to corrupt data have been eliminated and slow processing times for high multiplicity and noisy events have been greatly improved over the past year. These improvements will directly benefit the reconstruction of physics collision data in the future.

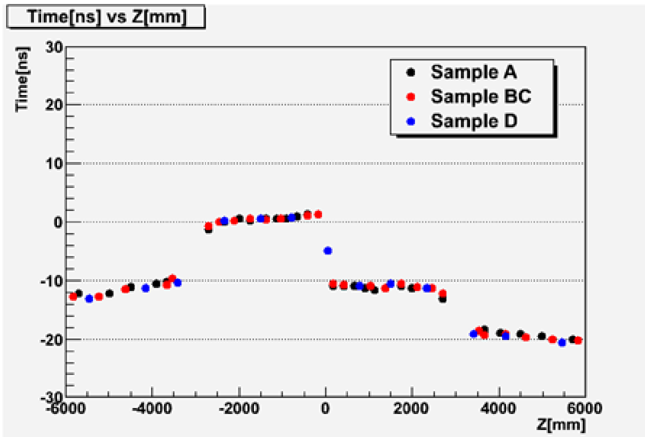

Fig. 12. Cell timing for the tile calorimeter in single beam events, including "beam splash" events. The beam was incident from negative Z, so first a time-of-flight correction has been applied. The different events also have their times normalized to a common reference. The corrected times are shown for all cells in the three sampling layers, and the four different partitions. A laser calibration system had previously been used to calibrate the cell times within each partition. So, using these events we confirm the timing within a partition, and can measure the time difference between partitions. (The laser calibration has recently been extended to measure the time difference between partitions, and is being compared to the "beam splash" results.)

III. Conclusions

The ATLAS reconstruction software, closely following the commissioning of the ATLAS detector, is being commissioned with all available physics data. The full offline reconstruction chain is in place providing reconstruction for the high level trigger, monitoring, event displays, calibration and alignment studies, and offline analysis. At the same time we commission the ATLAS computing and grid environment. The reconstruction chain is robust, having been exposed to many months of cosmic ray data and three memorable days of LHC single beam operations. ATLAS is operating with nearly all subdetectors integrated, and the unified reconstruction software has enabled detector performance studies to support hardware commissioning. We are prepared for, and very much looking forward to, first LHC collisions in 2009.

Acknowledgment

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